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Solutional and wind erosion forms on limestone in the Central Namib Desert

by

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with 1 figure, 5 photos and 3 tables

Zusammenfassung. Einige Abtragungsformen auf präkambrischen Marmoren und Kalken in der zentralen Namib werden beschrieben. Wegen der geringen Niederschläge und dem Charakter des Ausgangsgesteins ist die Desintegration zu einem groben „Marmor"-Sand die vorherrschende Verwitterung. Zwei weitere Abtragungsformen treten auf und werden im Detail beschrieben. Die erste Form besteht aus Rillenkarren, die an Westseiten von Kalkblöcken ausgebildet sind. und die anscheinend durch den Niederschlag des Nebels entstehen, der vom Atlantik landeinwärts verweht wird. Die Morphometrie dieser Rillenkarren ist ähnlich zu den Abmessungen an Rillenkarren aus anderen Teilen der Welt, die unter ganz anderen klimatischen Bedingungen entstanden. Die zweite diskutierte Abtragungsform besteht in winderodierten, subhorizontalen Kannelierungen. Diese entstehen bei Winden hoher Geschwindigkeit, die aus dem NE oder ENE kommen. Beide Abtragungsformen scheinen sich heute zu bilden und mit den heutigen atmosphärischen und Wind-Bedingungen verbunden zu sein.

Summary. This paper describes some erosional forms on pre-Cambrian marbles and limestones in the Central Namib. Because of the sparse precipitation and the nature of the rocks, granular disintegration into coarse "marble" sand is the most abundant weathering form. Two other erosion forms occur and these are described in detail. The first form is that of the rillenkarren which occur on the W facing sides of the limestone blocks and seem to be formed by precipitation from advective fog blown inland from the S. Atlantic. The morphometry of these rillenkarren is similar to rillenkarren morphometry described from other parts of the world and formed in very different climatic conditions. The second erosion form discussed is wind eroded sub-horizontal flutes; these are formed by winds of high velocity which blow from the NE or ENE. Both these erosion forms appear to be forming today and relate to the present atmospheric and wind conditions.

Résumé. Cet article décrit quelques formes d'érosion sur les marbres et les calcaires de l'age pre-Cambrian dans le Namib Central. La précipitation est très rare et les roches sont sux gros grains; sable de marbres sont très abondants.

Deux formes érosives sont discutées en détailles. La première sont les rillenkarren, qui se trouvent sur les blocs calcaires; ils sont en face des vents du sud-ouest et des brouillards de l'Atlantique du sud. Les caractèristiques morphometriques des rillenkarren sont analysées et sont comparées avec les rillenkarren dans les autres parties du monde. Les secondes formes érosives sont les cannelures du vents de nord-est. Les caractèristiques morphometriques des cannelures sont discutées. Il paraitrait que les rillenkarren et les cannelures sont actives pendant les conditions actuels et ils ne sont pas fossiles.

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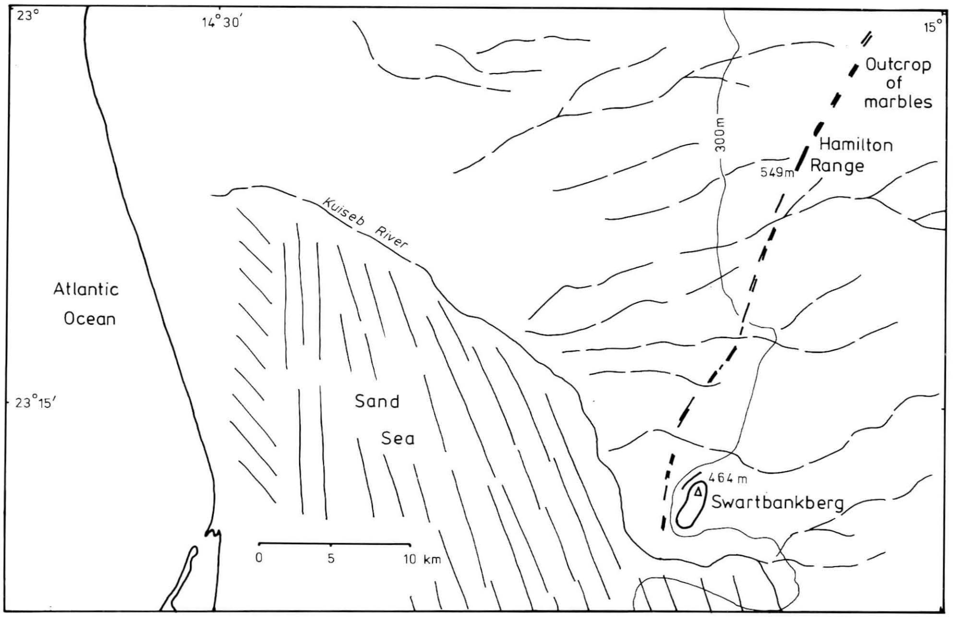
1 *Introduction*

In humid regions surface and subsurface solution of limestone produces a characteristic and well known suite of landforms. Such forms are generally regarded as absent in arid areas where limestone traditionally forms upstanding relief. However, even in hyperarid desert areas, such as the Namib desert in South West Africa, some solutional weathering of limestone does occur. In this paper we report our preliminary investigations of surface weathering forms and processes along a 50 km outcrop of Pre-Cambrian marbles and limestone in the central Namib desert.

The central Namib desert (fig. 1) is bounded to the south by the linear dunes of the Namib sand sea which end at the Kuiseb river. To the north are open gravel plains, consisting of coalescing alluvial and colluvial deposits, often cemented by gypsum or calcrete crusts, together with areas of thinly weathered bedrock. From the plains rise isolated or grouped inselbergs consisting of granites or gneiss, as well as the Pre-Cambrian marbles referred to above.

Climatically the area is dominated by the interaction of coastal and continental influences, giving rise to steep climatic gradients inland. The amount of rainfall decreases towards the coast which receives 15 mm per year. However, temperatures rise rapidly inland as the influence of the cold coastal waters of the Benguela current diminishes. Condensation of atmospheric moisture by the cold sea gives rise to an



advective fog, which is blown inland by N and NW winds. Fog precipitation is substantial, particularly at sites exposed to these winds, and reached 198 mm per year during the period 1976–1978 at Swartbank. Thus it is potentially an important moisture input for chemical weathering processes.

2 *Limestone weathering in the central Namib*

Pre-Cambrian dolomitic marbles of the Karibib Formation outcrop for some 100 km between the Kuiseb and Swakop rivers (Smith 1962). They dip steeply (60°–70°) westwards and form a low NE–SW to NNE–SSW trending cuesta for much of their length. In places more extensive outcrops occur, forming the Hamilton Range and the Swartbankberg. The marbles are variable in composition with purer more massive members standing up as lines of blocks or boulders 1–3 m high above the rather impure shaly or slaty members. The marbles are largely made up of clear crystals of calcite, with relatively little impurity. They are generally coarse-grained. In thin section they can be seen to be somewhat heterogeneous in grain size – consisting of a mixture of quite large (up to 3 mm dia.) crystals with smaller ones. In the vicinity of Swartbank slightly finer grained beds occur; these beds are also more homogeneous and are made up of uniformly-sized crystals which form dense interlocking mosaics.

Mechanical disintegration appears to be the most widespread weathering process operating on the marbles. Granular disintegration in particular affects the heterogeneous and coarser grained crystalline limestones, which break down to form extensive spreads of coarse marble sand or "grus" on the western sides of the cuesta. Low grade metamorphism of the impure members of the Formation has produced a series of calc-schists, with many slaty bands. These break down primarily by sheeting and spalling along the cleavage planes to produce a coarse angular platy mantle of debris (photo 1).

The more homogeneous and finer grained members of the marbles are areally restricted. They have less insoluble residue, and weather more smoothly and appear to be unaffected by granular disintegration. They are covered, particularly on their western sides, by a brownish grey patina of algae and lichens which spreads over a host of small pits and surface etchings, presumably of solution origin. In the vicinity of Swartbankberg the western side of many boulders is covered by parallel rillenkarren, first described from this area and attributed to solution by Goudie (1972). Their morphometry was studied because of their similarity to rillenkarren in both temperate and tropical humid areas.

With the exception of the rapidly disintegrating impure marbles, all outcrops are polished and smoothed on their eastern and northern margins by wind blasting. Often there is a sharp boundary between a smooth sandblasted eastern and a rough western side to the boulders as photo 2 shows. Furthermore, in certain locations wind erosion also produces characteristic rilling or fluting of the marble, but this is of a very diffent nature from the solutional rillenkarren which often occur on the same or adjacent boulders. The morphometric characteristics of the rillenkarren and wind fluting are now discussed.

Photo 1. General view of the outcrop of the metamorphosed limestone area looking South toward the Kuiseb river.

3 *Rillenkarren*

The rillenkarren occur on the upstanding blocks of the finer and more homogeneous marbles; they are found always on the NW or W facing sides, i. e. facing the Atlantic Ocean and the direction of incoming advection fogs. They tend to form on the block surfaces in groups, each group occurring on a surface or block of distinct inclination (photo 3). Over 100 rillenkarren were measured in the Swartbank area. Each group was measured separately for length, width and maximum depth of each individual rillenkarre; in addition the slope and orientation of the rock surface on which they were developed was recorded. The figures of their morphometry are given in Table I.

There is a general relationship between the length of the rillenkarren and the slope of the rock surface – as has been observed by DUNKERLEY and HEINEMANN et al. (DUNKERLEY 1979; HEINEMANN 1977). Rillenkarren length is usually greatest on slopes between 40–65°; DUNKERLEY, for instance, at Cooleman Plain in Australia found that rillenkarren "do not occur (or are very rare) on greatly sloping rock surfaces. . .."; (p. 336); GLEN & FORD in their simulation experiments found that

Photo 2. Contrasts in weathering on east and west sides of marble block.

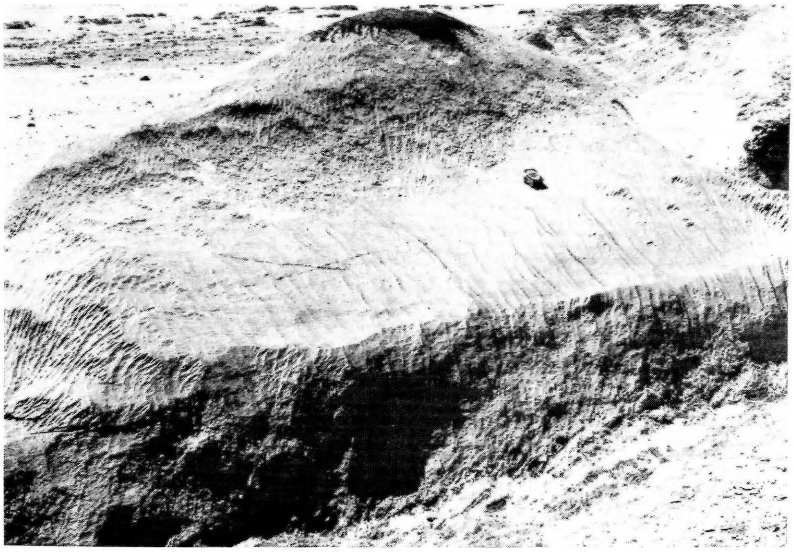


Photo 3. Rillenkarren occurring on fine grained marbles and facing South westwards.

Table 1

Slope Group	Mean Slope	Length mm	Width mm	Length/ Width ratio	Depth mm	Number
30–40°	33.4	172.95	21.95	7.9	3.17	21
	(S.D. 3.43)	(S.D. 50.53)	(S.D. 3.46)		(S.D. 0.69)	
50–66°	54.75	207.14	29.85	6.94	2.96	47
	(S.D. 10.61)	(S.D. 41.56)	(S.D. 10.09)		(S.D. 0.69)	
10°	10°	180	27.5	6.6	1.5	3

the largest rillenkarren occurred on slopes between 50° and 65° (Glen & Ford 1980). This is the case at Swartbank. At Swartbank also there is a weak correlation between rill length and rill depth (0.81), i. e. the larger rills are also deeper. In general rill width is very constant as noted by Dunkerley (p. 335). Depths of rillenkarren are less that those recorded in other localities (approximately 3.00 mm) compared with average depths of 15 mm recorded by Heinemann et al. in Mallorca and of 25 mm in the Mulu area of Sarawak recorded by Osmaston (1980).

The significant feature about the morphometric characterisitcs of the rillenkarren in the Swartbank area is their general similarity to those recorded in climates with very different rainfall regimes. This bears out the comment by Dunkerley that rillenkarren are not purely hydrodynamically determined and are largely independent of the effective intensity of the rainfall within a site (p. 339). In all areas where rillenkarren occur they are never uniformly developed; this also suggests that they are related more to the physical chemistry of the solution process, particularly as it is determined by the rock texture and grain size.

The distribution and relationship of the rillenkarren to the other types of weathering features discussed in this paper, particularly the wind erosion flutes, indicate that the rillenkarren are forming today and are not fossil features. It is therefore likely that the water available for formation of the rillenkarren comes chiefly from the advective fogs. It is possible that their formation is assisted by the high salt content of the fog, 120 kg/ha, Erikson (1958) and Goudie (1972). An analysis of waters of two nearby springs on the E side of Swartbankberg show not only the highly calcareous nature of the waters but also their very high salinity (table 2).

Table 2 Swartbank Springs – Mineral content in ppm.

	Ca	Mg	Fe	Al	Ma	Sr	Si	K	Na
Spring 1	925	410	0.4	0.0	0.1	5.8	5.1	140	7,000
Spring 2	920	420	0.4	0.0	0.1	5.7	4.8	140	7,000

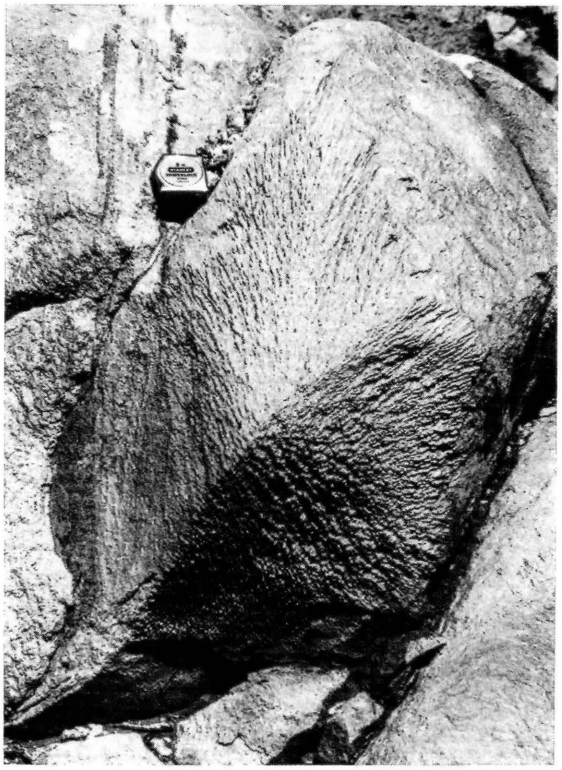


Photo 4. Wind etched grooves on blocks facing North East.

4 *Wind erosion flutes*

Wind erosion forms are common on the more resistant limestones throughout the investigated area. They do not appear to occur on other rock types, which weather mechanically too rapidly to preserve such features; the exceptions are the dolerites, which outcrop around Swartbankberg as rectangularly jointed dykes, individual boulders of which preserve extensive wind faceting of northeast facing margins (SELBY 1977).

The most widespread effect of wind erosion on the marbles is removal of the weathered east facing surface of boulders to a height of up to 2 m above gound level, exposing and keeping exposed fresh unweathered rock. The general effect is to smooth and polish the rock surface. Locally however weaknesses are exploited and small pits up to 5 cm deep are excavated. No signs of faceting of marble boulders were noted.

Locally where the more homogeneous and fine grained marbles outcrop, wind action produces a near horizontal series of flutes (photo 4) or parallel sharp crested grooves in the rock surface. These are frequently associated with the rillenkarren described above, but may also occur on their own, as for example in the area immediately north of Swartbankberg. Table 3 illustrates the main morphometric characteristics of the flutes. From this it will be seen that they have a mean width of 5.5 mm and a mean depth of 2 mm. In the locality investigated they have a NE–SW trend, but north of Swartbankberg similar features on flat boulders may trend ENE–WSW. Wind fluting is rare on the lower parts of the eastern sides of the boulders and seems to be found more commonly on their tops and western sides, and on their northern ends, and with a northeasterly orientation. Frequently the flutes run across the side slopes of the boulders which have angles of 32–54°, and may cut the rillenkarren. In detail, the flutes diverge around boulders from north to south and appear to mirror the expected pattern of wind flow over the boulders.

Table 3 Morphometric characteristics of wind flutes.

Site	Slope °	No. of flutes per 50 mm	Mean flute width mm	Orientation
1	36	9.25	5.41	45° E of N
2	45	7.50	6.70	45° E of N
3	32	7.30	6.85	30° E of N
4	53	11.50	4.35	40° E of N
5	32	9.00	5.60	40° E of N
6	54	9.50	5.26	20° W of N
7	33	9.30	5.38	40° E of N
Mean	40.71°	9.05 mm	5.65 mm	
S.D.	9.83°	1.40 mm	0.87 mm	

Comparisons with features elsewhere are difficult to make. Much work has concentrated on large scale features such as yardangs (e. g. McCAULEY et al. 1977) or on the form of individual stones (dreikanter etc). Additionally, in the Namib at least, earlier workers (e. g. HARGER 1914; RAND 1920) seem to have attributed to wind action features which probably result from salt crystallisation weathering. However, KAISER (1923) describes and illustrates fluting patterns of similar size to those at Swartbank on foyaite boulders in the southern Namib. These also show similar patterns of flow over and around the boulders. There are also some similarities in form between the flutes from Swartbank and the grooves and flutes cut in granite boulders in Wyoming described by SHARP (1949) and fluted limestone cobbles and boulders from Death Valley, California described and illustrated by MAXSON (1940).

The orientation of the sandblast and flute features described above clearly indicate formation by winds from NNE to E. Analysis of winds recorded autographically by the Desert Ecological Research Unit at a station 4 km east of Swartbankberg shows a bidirectional wind regime with 26% of winds blowing from NNW to N, and 23% from S to SW. Winds from NNE to E are less common and blow for only 8% of the time – mainly in the winter months of April to August. However, during this period they account for 16% of all winds blowing at velocities above the threshold for sand movement (16 kph). Further, winds from this sector account for 76% of winds at 31 kph and no less than 89% of all winds with velocities over 41 kph. During the period 1976 to 1978 53 hours of winds above this velocity were recorded, with an average velocity of 46 kph. The maximum wind speed recorded over an hour was 65 kph from the ENE.

Clearly the wind erosion features in the Swartbank area are aligned, not with the dominant or prevailing wind direction, but with the direction from which the strongest winds blow, as was observed by WHITNEY (1978) in Michigan. This implies that they are formed by high velocity winds with a dense curtain of saltating sand picked up from the many alluvial fans and spreads in the area. Only these winds can impart a sufficient impact velocity to the sand to enable it to erode.

The origin of the flutes is more difficult to explain. The regularity of the form and their even spacing implies a regularity in the wind flow. They also occur on the western sides of boulders, away from the strongest winds. One explanation may be found in WHITNEY (1978) who suggests that vorticity may play an important role in wind erosion by promoting the impact of particles brought to the eroding rock surface by the aerodynamics of flow around the boulders. The pattern of the flutes described here, with their clear pattern of divergence and convergence and cross slope orientation, would seem to support this view. They thus represent patterns of erosion during the wind movement around the boulders of east and northeasterly sand laden winds.

5 *Conclusion*

The weathering features described in this paper result from two contrasting processes: solution of the surface by slow runoff of possibly saline moisture precipitated by fogs and of wind erosion by high velocity easterly and northeasterly winds.

Rillenkarren are restricted by the limited outcrop area of homogeneous and fine grained marbles, which resist mechanical disintegration. Coincidentally this lithology also permits wind fluting. On each boulder there is a delicate interplay between solution and wind erosion forms. In some cases it appears that wind erosion flutes were gaining at the expense of rillenkarren (photo 5), whilst in other examples algae- and lichen-covered wind flutes were observed. The exact nature of the interplay of wind and solution processes probably depends on the configuration and shape of the individual boulder and its micro-relief. It does not suggest any marked secular environmental change. Frequencies of strong easterly winds vary from year to year, and it is possible that a series of years of above average frequency and strength of these winds might be sufficient to remove a patina of algae and to develop or extend flutes. Conversely a decreased frequency of east winds might well enable surface weathering to break down flute patterns to facilitate the expansion of areas of algae.

This preliminary investigation of surface weathering forms on limestones in the central Namib indicates that mechanical disintegration is the dominant process in this environment but that on certain lithologies surface solution may occur, even in a hyperarid climate, as a result of fog precipitation. This suggests that fog precipitation plays an important role in rock weathering in many parts of the coastal

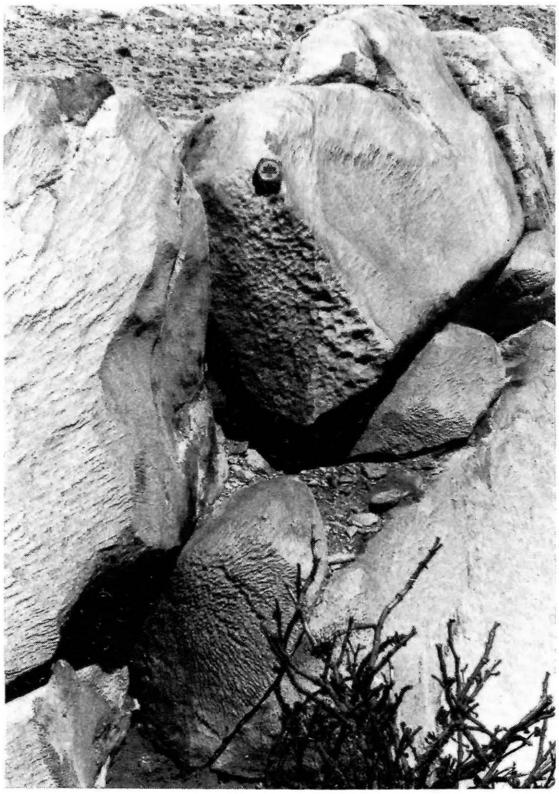


Photo 5. Blocks with rillenkarren and wind etched flutes, Swartbankberg.

Namib and in other coastal deserts affected by frequent fogs. Wind erosion by sand blast and vortical action is also an important process, but its effects are restricted in this case to the more homogeneous rocks, which are not affected by rapid mechanical disintegration.

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